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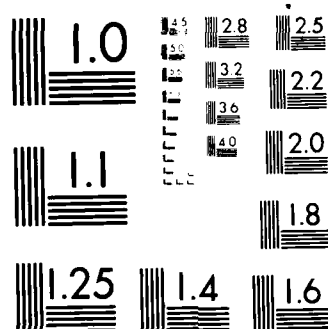
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AMMRC TR 83-20

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**CHARACTERIZATION OF SOME MATERIAL
PROPERTIES OF THE ABLATIVE NOSE CAP
OF THE M797 TRAINING ROUND**

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Judith Jenkins Kohatsu
METALS RESEARCH DIVISION

April 1983

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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ABSTRACT

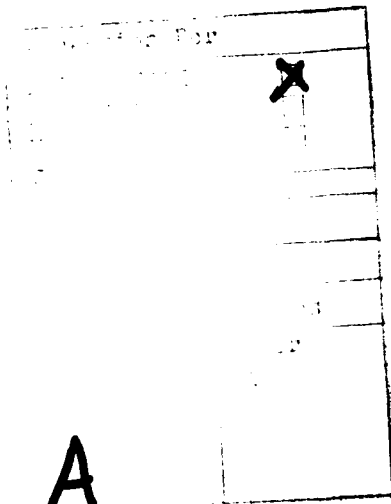
An ablative nose cap, being developed for the M797 tank training round, has failed to destabilize consistently during flight over a temperature range of -50°F to 125°F. In this study, the zinc alloy AG40A, comprising the cap, was characterized with respect to mechanical and thermophysical properties. The die-casting production method must be improved in order to obtain standardized nose caps. This standardization will limit the variables controlling destabilization, but of itself, will not correct the flight inconsistencies. The degradation of mechanical strength of the zinc alloy is rapid, with minor increases in temperature; therefore, the lack of success in achieving destabilization is not directly a function of the material selected. The process of ablation, however, impedes the overall heating of the nose cap, and therefore delays the degradation of mechanical properties. The times available at elevated temperatures may be insufficient to achieve the desired property decay over the full range of service temperatures. The ablative process should be limited, if not entirely avoided, in order to achieve sustained elevated temperatures.

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INTRODUCTION

An ablative nose cap or tip is being developed for the M797 training round with the objective of limiting the range of the projectile for safety reasons. The M797 training round is a 105-mm round consisting of a zinc-alloy nose cap, a tri-sected steel shaft (or petals), and stabilizing fins. In theory, the nose cap ablates during flight after firing, aerodynamically destabilizing the training round after it has traveled approximately 3000 meters. In practice, the destabilization has not occurred consistently when the round is fired over a temperature range from -50°F to 125°F . Most particularly, destabilization does not occur at the lower temperatures. The assistance of AMMRC was sought by ARRADCOM in characterizing the material properties of the zinc alloy used in the cap as an aid to the analysis of the ablative process.

The nose cap is shown schematically in cross-section in Figure 1. The nose cap is thought to destabilize in flight by weakening in section A, presumably by material loss due to ablation, or in section B, by aerodynamic heating effects. The nose cap is formed from the zinc alloy AG40A by die-casting. This is primarily a Zn-4% Al alloy with minor additions of Cu and Mg. The nominal alloy composition is given in Table 1.

In order to model more accurately the behavior of the tip during flight, mechanical property data and thermophysical data were needed. Such data were to be utilized in a computer computation which would then better predict behavior under a variety of firing conditions. The mechanical properties to be measured as a function of temperature included hardness, yield strength, ultimate tensile strength, reduction in area, and elongation as well as elastic modulus. Thermophysical data to be considered would be latent heat of fusion, the melting range, and specific heat.

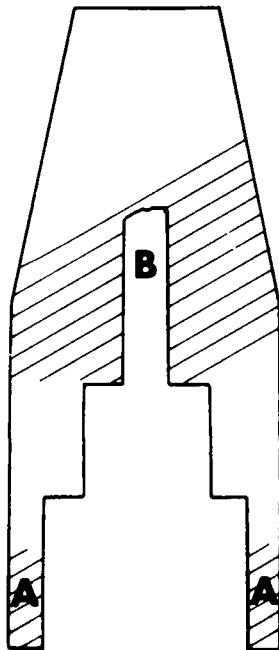


Figure 1. Schematic Cross-Section Diagram of M797 Nose Cap (Not to Scale).

Table 1. ZINC ALLOY AG40A
Nominal Composition

	Weight %
Cu	0.01 max
Al	3.9-4.3
Mg	0.025-0.05
Pb	0.004 max
Cd	0.003 max
Sn	0.002 max
Fe	0.075 max
Zn	Remainder

Additionally, the microstructural features of the die-cast tip were to be considered. The "soundness" of the die-casting could also affect the mechanical strength of the nose cap. The microstructure could serve as a monitor of the die-casting operation since it is sensitive to both thermal and compositional variations during the casting operation.

PART I. MANUFACTURE AND MATERIAL PROPERTIES OF THE NOSE CAP

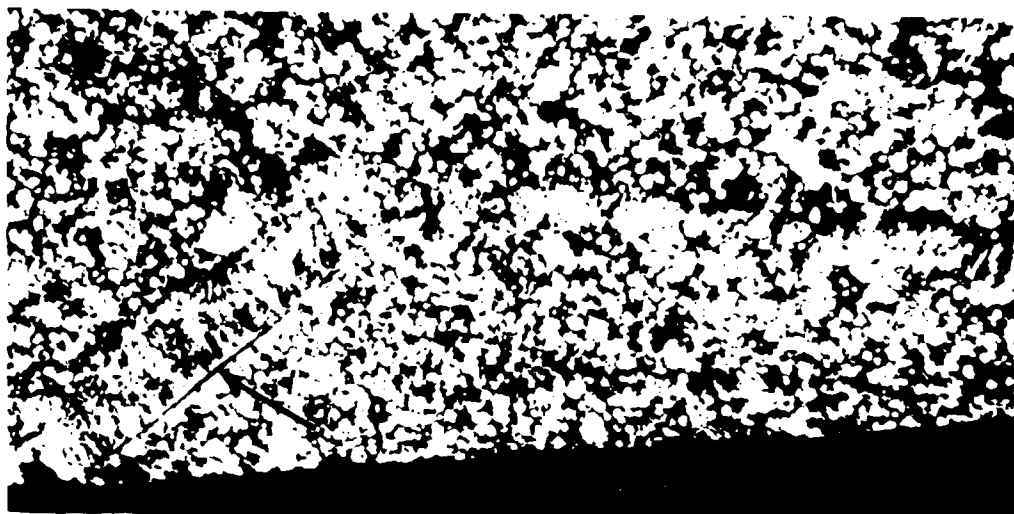
The Die-Casting Operation

The nose caps were cast in a single-cavity die* by Southeastern Diecasters of New Shrewsbury, PA. The cycle time was approximately 15 seconds, resulting in an average production rate of four nose caps per minute. Initially, samples were obtained from four different production runs, dating from November 1979 through May 1980. All material used in these runs had been certified as zinc alloy AG40A. These samples were sectioned longitudinally and examined metallographically.

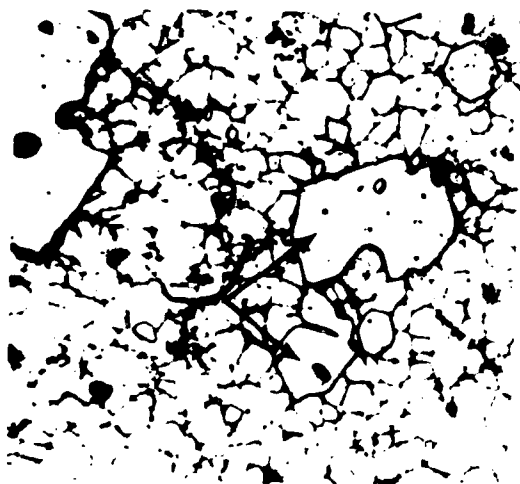
The six samples examined were found to vary widely in microstructure. All samples contained significant porosity. Although the majority of the porosity found above the machined slot (section B, Figure 1) was shrinkage porosity, gas porosity was also rather evenly distributed throughout the cross-section. The size and distribution of the two phases present were not consistent from one nose cap to the next. Evidence was found of cold shuts (Figure 2a), secondary phases due to impurity pickup (Figure 2b), and irregular solidification (Figure 2c). A representative example of the nose cap cross-section is shown in Figure 3, showing both the concentrated and uniformly distributed porosity.

These microstructural defects can be minimized by more careful die-casting procedures. The gas porosity arises from the absorption of a reducing gas, most likely hydrogen. It occurs in two stages of operation: initially in the melting stage illustrated by smooth spherical porosity, evenly distributed throughout the

*The die was initially built with two cavities, but during design modifications, one cavity was sealed off.



a. Cold shut caused by locally chilling the mold. Mag. 500X.



b. Impurity pickup. In this case, Fe is picked up forming a hard brittle Fe-Al compound. Mag. 350X.



c. Irregular solidification. Fine structure is surrounded by coarse grains which are, in turn, surrounded by very fine grains. Mag. 350X.

Figure 2. Die Casting Defects.

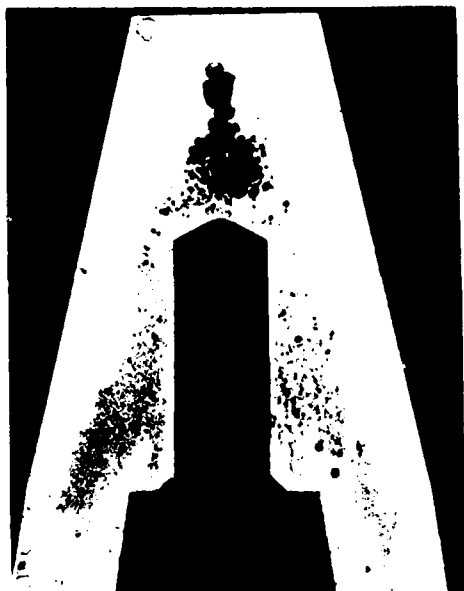


Figure 3. Coarse and Fine Porosity Distribution.
Mag. 3X.

casting, and secondly, during injection due to entrainment, illustrated by the uneven concentration of porosity. These flaws can be reduced by several simple steps:

1. the use of clean and dry ingot material,
2. melting rapidly, without overheating - a casting temperature of 735-780°F controlled to within $\pm 10^\circ\text{F}$, is recommended, in excess of 800°F is deleterious,
3. degassing the molten material before injection,
4. the use of dry fluxes,
5. ensuring that spent gases and moisture (e.g., humid conditions) do not contact the molten metal, and
6. increasing the injection pressure (minimum 1500 psi).¹

The problems of shrinkage porosity, hot tearing, and cold shuts are all related to the die temperature and the cycle time. Shrinkage porosity results from a local overheating of the die, while cold shuts arise from a local undercooling of the die. The mold temperature must be adequately and uniformly maintained in the range of 325-475°F with cooling supplied to those areas which tend to overheat. The die temperature should be kept within $\pm 10^\circ\text{F}$ of the selected temperature. Additionally, the gate to the mold might be enlarged to feed the die cavity better and faster. Increasing the cycle time will increase the solidification time for the casting, allowing additional time for equilibrium to be approached.¹

The impurity pickup which occurred in these samples was of iron, most probably from the holding pot. This can occur when the melt is overheated and some of the aluminum is oxidized, thus causing a decrease in the aluminum content. As the

1. *Temperature Ranges, Controls, and Pressures.* Metals Handbook, ASM, v. 5, 1970, p. 444.

aluminum content decreases, so does the scavenger action of the iron. Less Fe-Al intermetallic is formed and removed in the slag and more iron is retained in the melt to form brittle inclusions upon solidification.

Experimental Data

Mechanical Property Data: At the request of ARRADCOM, testing of the zinc alloy AG40A was undertaken to determine mechanical properties as a function of temperature. Since this alloy is rarely die-cast for products utilized much above room temperature, no extensive mechanical test data existed in the literature. All mechanical property data were collected on gravity cast bars provided by Southeastern Diecasters from material cast in May 1980. It should be noted that these bars are not die-cast, but gravity-cast, resulting in a significantly larger grain size. The mechanical property data collected should, nevertheless, be indicative of the performance of die-cast properties.

The mechanical property data was gathered by the Engineering Test Laboratory's Materials Properties Branch at AMMRC, from temperatures of -50°F to 450°F. The high temperature range (i.e., above room temperature) was achieved by submerging the sample in heated oil, equilibrating, and testing. The upper temperature limit represents the highest temperature at which oil might be safely used. The low temperature regime was reached with a dry ice and alcohol bath. The first data taken were "hot" hardness data which are presented in Table 2 and Figure 4. These data indicate that the hardness of zinc alloy AG40A decreases rapidly beyond 100°F. At 250°F the hardness had decreased from a room-temperature value of HRF 85 to HRF 45, a 47% decrease. No measurement was possible at the maximum testing temperature, as the material was so soft that upon testing the indenter sank up to its shoulders.

Table 2. HARDNESS OF AG40A AS A FUNCTION OF TEMPERATURE

Temperature, °F	Hardness* Rockwell, °F
-50	89.3
-25	87.8
0	83.0
70	85.0
100	81.4
200	65.5
250	42.4
300	25.4
450	†

*Average of six readings
Load 60 kg 1/16" ball

†Material too soft for testing

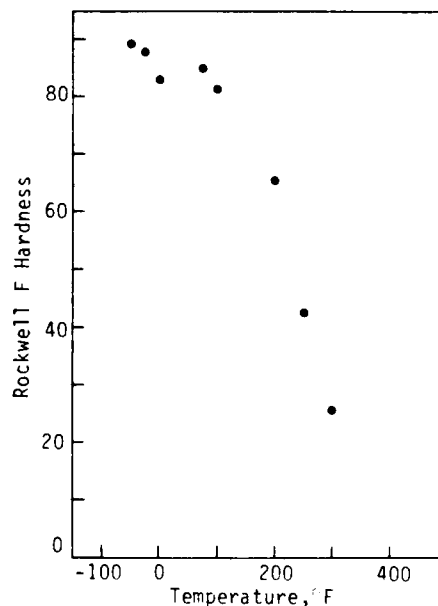


Figure 4. Hardness as a Function of Temperature.

The tensile data for the alloy are presented in Table 3 and Figure 5. The highest value of the ultimate tensile strength occurs at -50°F with a value of 40.4 ksi. The tensile strength falls steadily until $\sim 70^{\circ}\text{F}$, then decreases extremely rapidly, falling to 52% of its room temperature value at 300°F . At 450°F , the maximum testing temperature, the strength is 20% of the room temperature value. The low temperature (-50°F) strength is nearly 7% greater than the room temperature ultimate. The percentage elongation (2 inches) remains essentially constant ($\sim 2-4\%$) below, and in the vicinity of room temperature. However, it more than quadruples in value upon heating to 150°F and steadily increases thereafter. It should be noted that above 200°F , creep becomes an operative deformation mechanism. The elastic modulus data are scattered. Above 450°F , no elastic region can be detected on the stress-strain curve.

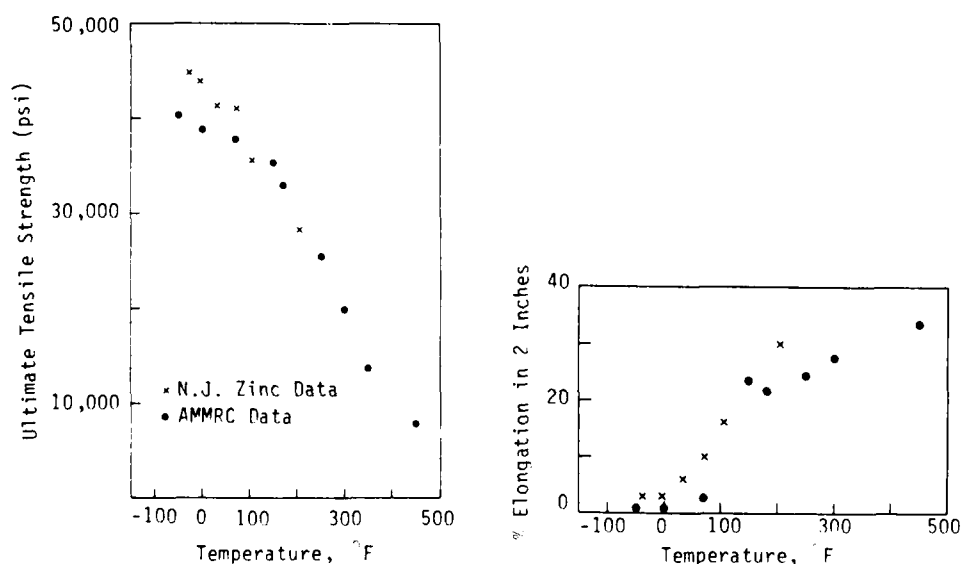
Table 3. TENSILE PROPERTIES OF AG40A

Temperature $^{\circ}\text{F}$	Yield Strength at 0.1% ksi	Yield Strength at 0.2% ksi	Ultimate Tensile Strength ksi	Young's Modulus psi	Elongation* %	Reduction in Area %
-50	30.60	35.00	40.40	10.3×10^6	0.8	1.8
0	27.50	32.20	38.90	12.0×10^6	0.9	1.8
70	27.25	30.85	37.85	10.4×10^6	2.8	3.6
150	23.70	27.15	35.20	13.6×10^6	23.2	49.0
170	19.40	22.50	32.90	10.8×10^6	21.5	43.0
250	17.15	19.05	25.35	13.8×10^6	24.2	39.8
300	14.95	17.30	19.80	12.6×10^6	27.2	34.1
350	10.35	11.65	13.60	10.6×10^6	15.8 [†]	32.4 [†]
450	†	†	7.90	†	33.4	50.9

*Elongation, in 2 inches

[†]Specimens bent, % elongation and reduction in area are approximate

†Continuous yielding, yield strengths and modulus unobtainable



a. Ultimate tensile strength b. Percentage elongation in 2"

Figure 5. Mechanical Properties as a Function of Temperature.

Thermophysical Data: In order to facilitate computer modeling of the nose cap, various thermophysical data were needed. Initial computer simulations indicated that useful parameters would be the melting temperature range, the latent heat of fusion, the specific heat capacity, the linear thermal expansion coefficient, and the thermal conductivity. Trial runs of the computer model tested the sensitivity of the model to thermal conductivity by substituting the conductivity of pure copper (398 w/mK) for that of pure zinc (113 w/mK). No significant difference was demonstrated, therefore, no new measurements were conducted. The insensitivity of the model to thermal conductivity may indicate that when ablation occurs, the surface temperature of the nose cap and the interior temperature of the nose cap remain relatively unchanged. Thus, thermal degradation of the mechanical properties by an increase in the average temperature of the nose cap body may not occur. Published data from the New Jersey Zinc Company on thermal conductivity is reported in Table 4.

The latent heat of fusion and the melting range were determined by differential scanning calorimetry with the cooperation of the Organic Materials Laboratory at AMMRC. The phase diagram for the zinc-aluminum system (the zinc-rich end) is presented in Figure 6 with the approximate composition of alloy AG40A as noted. Upon heating from room temperature, the material undergoes solid-state transformation (eutectoid), and then a eutectic transformation to the liquid state. The eutectoid reaction occurs at 281.5°C (538°F) with an endothermic enthalpy of reaction of 1.98 cal/gm (3.56 BTU/pound). The alloy begins to melt at 381°C (718°F), the eutectic temperature. Melting is complete at 388°C (730°F) above which the alloy is a single phase. The "effective" latent heat of fusion is endothermic, with a value of 26.50 cal/gm (47.7 BTU/pound). This value of latent heat agrees within experimental error with the previously reported value of the latent heat of fusion (by New Jersey Zinc Company) of 43 BTU/pound.

The specific heat capacity data generated in this experiment proved unusable. An alternative approach could be to apply the methods of K.K. Kelly² and approximate the specific heat of the alloy by the sum of the specific heats of its elemental constituents. Thus, for reasonably dilute solutions,

$$c_{p\text{alloy}} = X_{\text{Mg}} c_{p\text{Mg}} + X_{\text{Cu}} c_{p\text{Cu}} + X_{\text{Zn}} c_{p\text{Zn}} + X_{\text{Al}} c_{p\text{Al}}$$

where X_{Mg} are the weight fractions and $c_{p\text{Mg}}$ are the elemental heat capacities. The heat capacities of the elemental constituents are well described over a large temperature range by an equation of the form:

$$c_p = A + b T + c T^{-2} \text{ (cal/°K mole).}$$

The relevant equations for Mg, Cu, Al, and Zn are given in Table 5. The calculated value for this alloy at 300°K by the approximation, 0.095 cal/gm C, is in good agreement with the value cited by the New Jersey Zinc Company of 0.10 cal/gm C, the origin of which is unknown.

Due to equipment failure, the measurement of the linear thermal expansion coefficient of alloy AG40A was not pursued. However, the New Jersey Zinc data for this alloy is given in Table 4.

2. KELLY, K. K. *Contributions to the Data on Theoretical Metallurgy X High-Temperature Heat-Content, Heat-Capacity, and Entropy Data for Inorganic Compounds*. Bureau of Mines Publication 476, U. S. Government Printing Office, Washington, DC, 1949.

Table 4. THERMOPHYSICAL PARAMETERS OF ALLOY AG40A

Property	
Eutectoid Temperature	281.5°C (538°F)
Latent Heat of Eutectoid Reaction	1.98 cal/gm (3.56 BTU/pound)
Eutectic Temperature	381°C (718°F)
Liquidus Temperature	388°C (730°F)
"Effective" Latent Heat of Fusion	26.50 cal/gm (47.71 BTU/pound)
Specific Heat	0.10 cal/g/C*
Thermal Conductivity	0.27 cal/sec/cm ² /cm/°C at 18°C*
Thermal Expansion	0.000274/°C (0.000152/°F) +

*Die-Casting by H. H. Doehler, McGraw Hill, 1951, p. 283.

Table 5. SPECIFIC HEAT CALCULATION²

Zn		
from 298°K to melting point		
$c_p = 5.35 + 2.40 \times 10^{-3} T$		cal/mole°K
from melting point to 1200°K		
$c_p = 7.50$		cal/mole°K
Al		
from 298°K to melting point		
$c_p = 4.94 + 2.96 \times 10^{-3} T$		cal/mole°K
from melting point to 1300°K		
$c_p = 7.0$		cal/mole°K
Mg		
from 298°K to melting point		
$c_p = 6.14 + 1.50 \times 10^{-3} T - 0.78 \times 10^{-5} T^2$		cal/mole°K
from melting point to 1100°K		
$c_p = 7.40$		cal/mole°K
Cu		
from 298°K to melting point		
$c_p = 5.41 + 1.50 \times 10^{-3} T$		cal/mole°K
from melting point to 1600°K		
$c_p = 7.50$		cal/mole°K

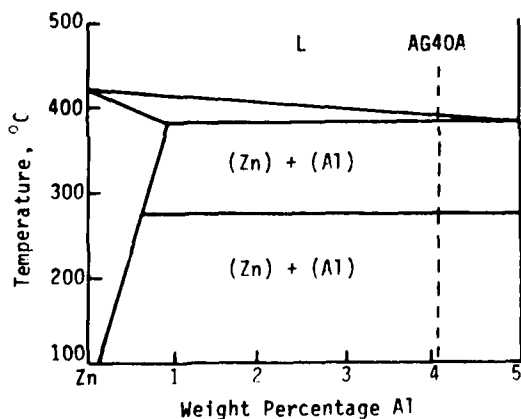


Figure 6. Phase Diagram Zn-Al System (Zinc-Rich End).

CONCLUSIONS

From this study of zinc die-casting alloy AG40A and its application as a nose cap for the M797 training round, it is apparent that the die-casting procedures currently employed are not adequate to produce standardized nose caps. Tighter controls on both the melt temperature (735°F - 780°F) and the mold temperature (325°F - 475°F) are needed. In addition, it is necessary to pay strict attention to the cleanliness of the melt, particularly with regard to the pickup of moisture from the environment. Redesign of the mold itself may also facilitate more reproducible products. It is recognized that these procedures will only limit the variables affecting flight destabilization, and will not directly correct the flight inconsistencies. It is also noted that these tighter controls may result in higher cost per nose cap. However, until flight destabilization is achieved and understood over the entire firing temperature range, such tighter production controls are necessary.

From the compilation of the mechanical property data as a function of temperature, it is evident that this material rapidly loses its strength at relatively minor increases in temperature (e.g., at 100°F), and at temperatures approaching 500°F is incapable of sustaining any significant load. However, it should be noted that for temperatures below room temperature (down to -50°F) there is nearly an 8% gain in strength. Thus, the nose cap may be stronger at these lowered temperatures than previously anticipated.

This alloy certainly experiences the degradation of mechanical properties with increasing temperature as desired. In fact, this degradation occurs at temperatures which are only 40% of the temperature the nose cap is to experience in use. The lack of success in achieving aerodynamic instability by ablative destruction of the nose cap may indicate that either the projected temperatures are not reached, or if reached, are not sustained for sufficient times.

RECOMMENDATIONS

1. Tighten up die-casting procedures so that a standardized product is achieved, thus eliminating the production procedure as a variable.
2. More carefully correlate material (and die-cast) lot with performance. To date, no correlations of this nature can be made between a successful firing and a particular die-cast lot, and thence to microstructural characteristics and mechanical properties.

PART II. FIELD DATA AND PLASMA JET SIMULATION

Firing summaries from trials of the M797 round were provided by ARRADCOM. Test firings were made under arctic, moderate, and tropical conditions (-20°C , 20°C , and 40°C). Some of the tests were conducted with both the cartridge and the projectile conditioned at approximately ambient conditions. Other tests were conducted in a "mixed-mode" manner, in which the projectile and cartridge were preconditioned at temperatures other than ambient, e.g., preconditioning at arctic temperatures, but actually firing in the desert. Firing data for which all components were essentially at the ambient temperature are presented in Table 6. (The non-ambient, mixed-mode data were excluded as it is felt this might obscure "material effects.")

Table 6. FIRING TEST DATA, AMBIENT CONDITIONS

Air °C	Temperature Nose Cap °C	Cart. °C	Number Fired	Bu*	No Bu	Lost	Muzzle Velocity m/sec	Time sec	Breakup Range m	Special Conditions	Comments
-21.9	-13.8	-13.8	5	0	4	1	1516				Failed
-24.7	-17.8	-17.8	4	2	2	0	1510	3.47	4237	Ni/Cr Plated	Good
15.6	21.1	21.1	4	3	0	1	1513	1.8	2352		Too Short
15.6	21.1	21.1	10	10	0	0	1558	1.6	2174		Too Short
15.6	21.1	21.1	2	2	0	0	1567	2.1	2923	Ni/Cr Plated	Close
26.7	21.1	21.1	1	1	0	0	1517	1.78	2754	Ni/Cr Plated	
35.3	21.1	21.1	7	7	0	0	1552	1.9	2664	Ni/Cr Plated	
35.0	21.1	21.1	10	10	0	0	1551	2.22	3012	Ni/Cr Plated	Good
40.6	51.7	51.7	5	5	0	0	1629	1.6	2310	Steel Tip 2.79-mm Wall	Failed

*Bu = Breakup

Cone Angle = 12.5°

Wall Thickness = 4.70-mm

The limited data show the most promising performance (i.e., breakup in or near the specific range) by the Ni/Cr plated zinc nose caps. Under arctic conditions, breakup occurs within the specified range. In moderate and tropic regimes, the breakup occurs too soon, but occurs closer to the specified range than other projectiles.

It is felt that the Ni/Cr plating is serving two functions. First, it provides good heat transfer into the zinc alloy body. Secondly, it prevents the ablation of the zinc, thus limiting heat loss. The suspected mode of failure of the nose cap is a mechanical failure of the thin wall at the rear of the cap. The plasma jet simulations performed and filmed by AVCO (Wilmington, MA) for ARRADCOM support this thesis. The unplated zinc alloy nose cap is observed to ablate until only a small ring of the original cap (the rear part) is left surrounding the petals. Failure had originally been predicted when the machined slot (see Figure 1) forward of this position was exposed. The Ni/Cr plated nose cap retained its shape until the plating fractured (probably from the differences in thermal expansion of the plating and the body). Failure was a mechanical one from the rear. The original nose cap shape was not as eroded as the unplated version at the time of failure.

CONCLUSIONS

Initially, it was intended that the nose cap of the M797 training round ablate and fail under mechanical loading by the loss of cross-sectional area (material loss) and/or a degradation of mechanical properties at the elevated projectile temperature. In light of the data gathered, it appears that ablation will hinder the degradation of mechanical properties. As a volume of material (V_1) is heated to the point of melting and subsequently ablated, an amount of heat (Q) is removed from the underlying material, thereby preventing a significant temperature rise in the material that remains. When the volume (V_1) ablates, and is removed from the nose cap, the underlying volume (V_2) is exposed. The volume (V_2) now requires an additional heat input (Q) to continue the process. This is repeated as the nose cap incrementally recedes. Thus, the heat input produced by aerodynamic

friction does not effectively raise the average temperature of the wall of the nose cap. When ablation is prevented by the Ni/Cr plating, the heat input can be used to raise the temperature of a greater volume of the projectile to a higher average temperature. Thus, conditions are improved for the degradation of mechanical properties.

RECOMMENDATIONS

1. Avoid the use of an ablative outer material as the process of ablation removes heat from the body, thereby preventing its temperature rise.

2. Consider the use of a "skin" (nonablating) material to hold the shape of the projectile until mechanical instability occurs, i.e., until the strength of the skin and the "fluid" beneath is less than the applied stress. (The Ni/Cr data is suggestive.)

3. Avoid utilizing a process which requires a phase change of the material involved (e.g., solid→liquid). Such processes require a finite time at the given reaction temperature. Such times are not available with zinc alloy AG40A in the approximately 2.5 seconds prior to the required breakup.

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CHARACTERIZATION OF SOME MATERIAL PROPERTIES
OF THE ABLATIVE NOSE CAP OF THE M797

TRAINING ROUND - Judith Jenkins Kohatsu

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Key Words

Technical Report AMMRC TR 83-20, April 1983, 14 pp -

illus-tables, D/A Project 201201900GNC,

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Zinc alloys

Mechanical properties

Ablation

An ablative nose cap, being developed for the M797 tank training round, has failed to destabilize consistently during flight over a temperature range of -50 F to 125 F. In this study, the zinc alloy AG40A, comprising the cap, was characterized with respect to mechanical and thermophysical properties. The die-casting production method must be improved in order to obtain standardized nose caps. This standardization will limit the variables controlling destabilization, but of itself, will not correct the flight inconsistencies. The degradation of mechanical strength of the zinc alloy is rapid, with minor increases in temperature; therefore, the lack of success in achieving destabilization is not directly a function of the material selected. The process of ablation, however, impedes the overall heating of the nose cap, and therefore delays the degradation of mechanical properties. The times available at elevated temperatures may be insufficient to achieve the desired property decay over the full range of service temperatures. The ablative process should be limited, if not entirely avoided, in order to achieve sustained elevated temperatures.

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